ESTC 2008 - Active Optical Session

# Fiber-Based Laser Transmitter and Laser Spectroscopy of the Oxygen A-Band for Remote Detection of Atmospheric Pressure

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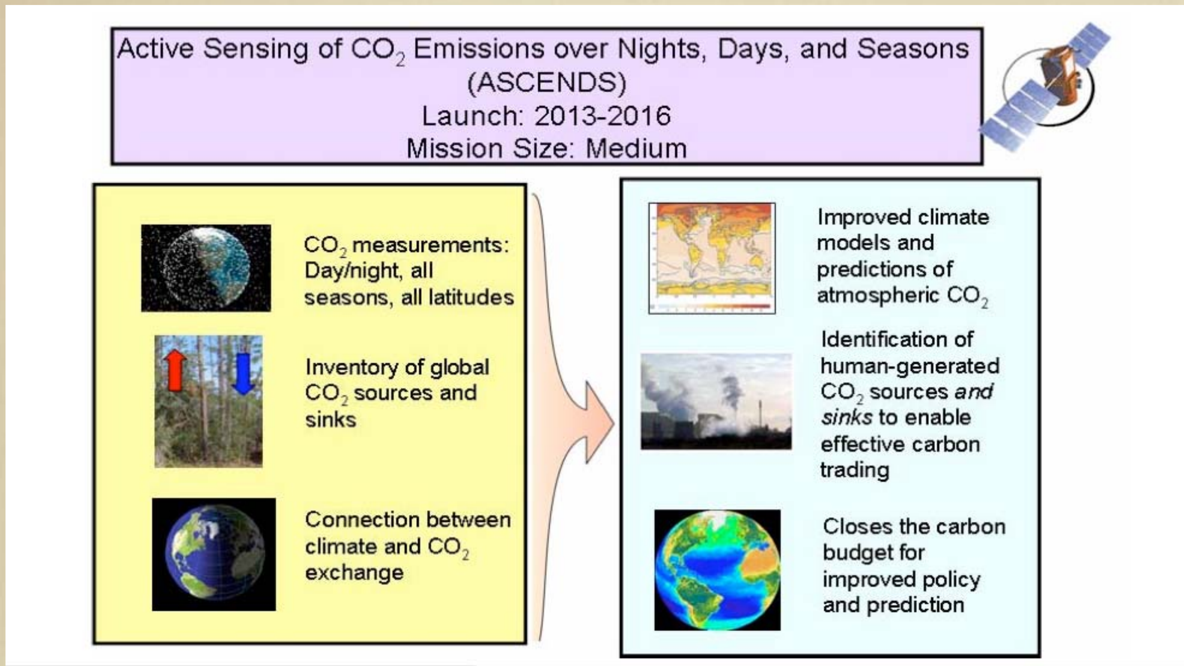
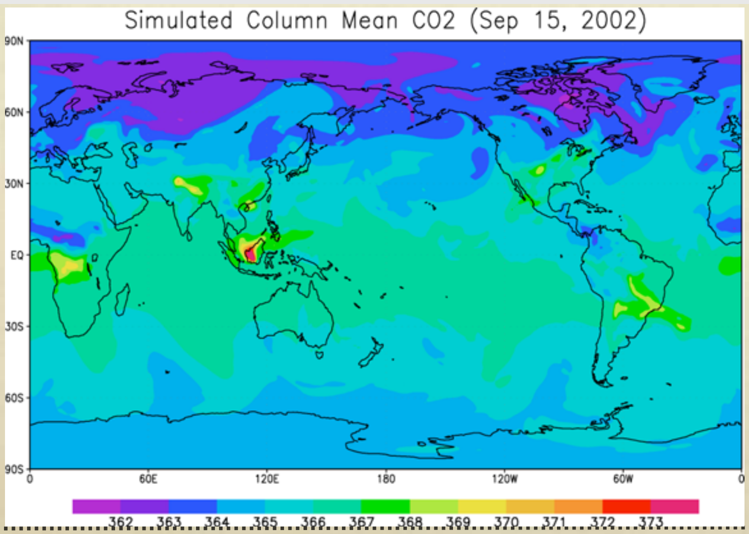
GSFC

# Outline

- Motivation / Instrument background
- Laser transmitter demonstration
- Spectroscopy in gas cell
- Power scaling transmitter with high SBS threshold EDFA
- Open path $O_2$ spectroscopy
- Future Work / Conclusions

# Motivation



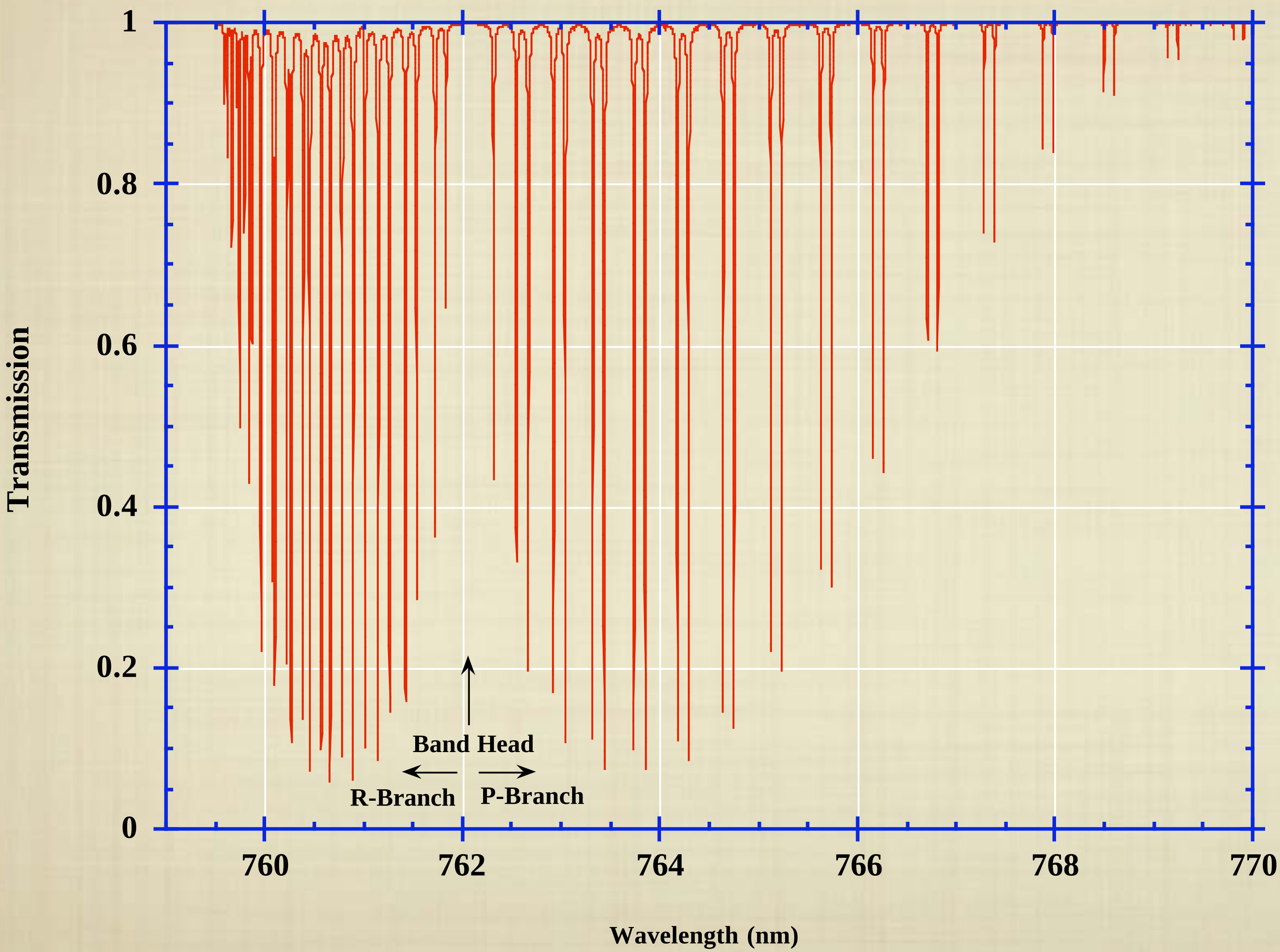

- High fidelity measurements of $CO_2$ are required to track sources and sinks in the global carbon cycle
- NASA-GSFC is working on a laser instrument designed to remotely measure $CO_2$.
- Largest error sources in this measurement are humidity and pressure. Pressure requirement is ~2 mbar.
- Global measurements of atmospheric Pressure are also applicable to weather prediction, atmospheric modeling and dynamic gravity field measurements.

# Background

- An instrument developed by Korb et al.* demonstrated ~2 mbar accuracy using a differential absorption LIDAR (DIAL) instrument in the oxygen A-Band. Instrument utility was limited by:
  - Laser technology (alexandrite) - difficult to field and inefficient.
  - DIAL technique - requires very high laser power for sufficient atmospheric backscatter
- This research addresses these issues by:
  - altering the instrument for hard target returns instead of atmospheric backscatter
  - developing a laser technology to address the subsequent requirements.

* Applied Optics **28** (15), 1989

# Oxygen A-Band



# Line Shape Analysis

$$T(\tilde{\nu}) = \exp[-K(\tilde{\nu}) \cdot L] = \exp\left[-\left(K_c + K_R(\tilde{\nu})\right)L\right]$$

Beer-Lambert Law with split Continuum and Resonant absorption Coefficients

$$K_R(\tilde{\nu}) = n \cdot S_j \cdot f$$

$n$ - number density

$S_j$ - Line strength parameter

$f$ - Line shape

$$f_D(\tilde{\nu}) = \sqrt{\frac{\ln(2)}{\pi}} \cdot \frac{1}{\gamma_D} \cdot \exp\left[-\ln(2) \cdot \frac{(\tilde{\nu} - \tilde{\nu}_o)^2}{\gamma_D^{\,2}}\right]$$

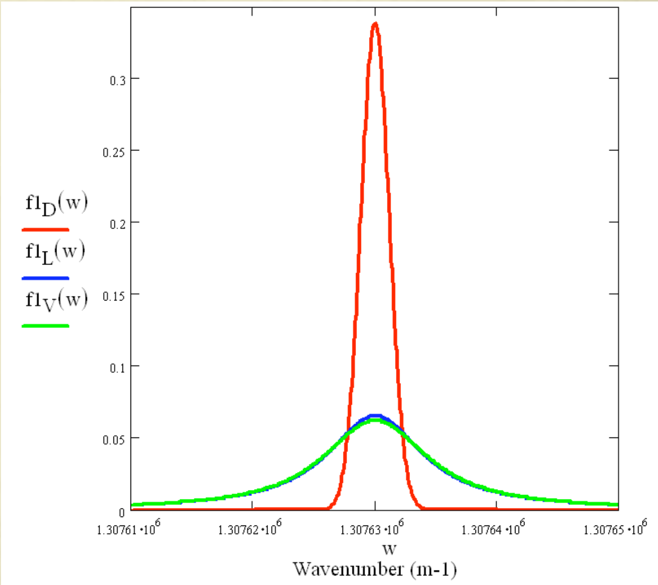
$$\gamma_D = \frac{\tilde{\nu}_o}{c} \cdot \sqrt{2 \cdot R \cdot \ln(2)\left(\frac{T}{M_{O_2}}\right)}$$

Temperature Broadening (Doppler, Gaussian)

$$f_L(\tilde{\nu}) = \frac{1}{\pi} \cdot \left[\frac{(\gamma_L/2)}{(\tilde{\nu} - \tilde{\nu}_o)^2 + (\gamma_L/2)^2}\right]$$

$$\gamma_L(\tilde{\nu}_o) = \gamma_{air} \cdot P \cdot \left(\frac{T_o}{T}\right)^{n_{air}}$$

Pressure Broadening (collision, Lorentzian)

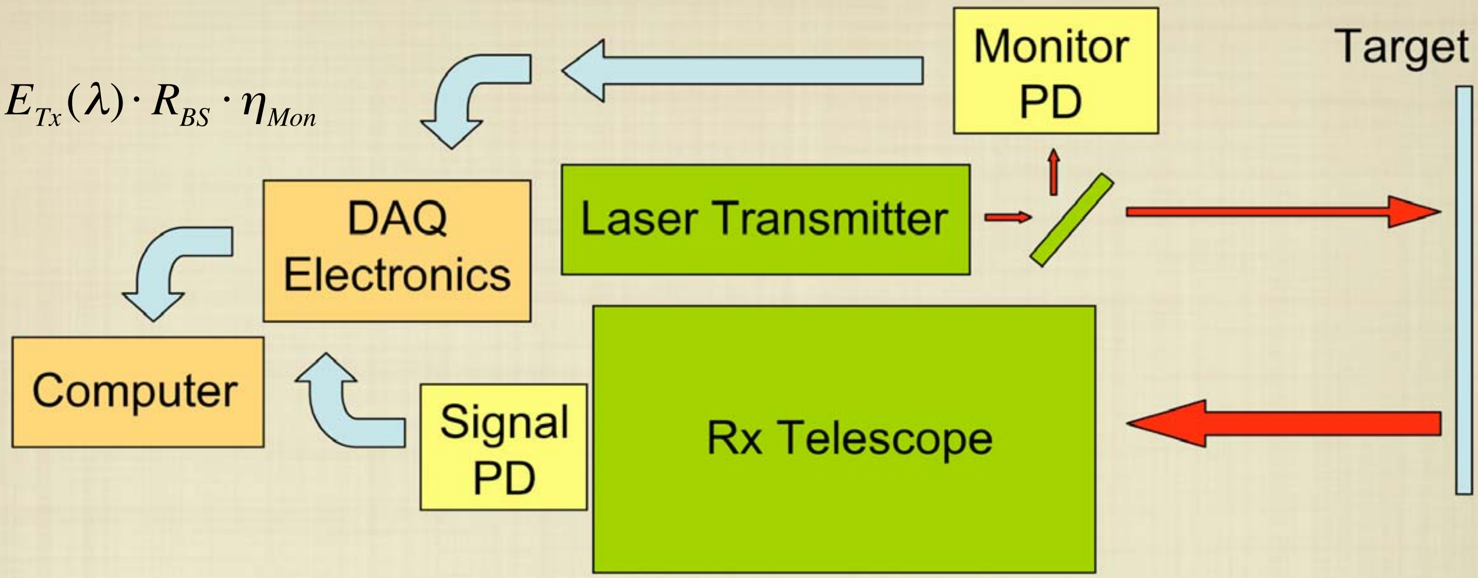



$$f_V(\tilde{\nu}) = \int_{-\infty}^{\infty} f_D(\tilde{\nu} - \tilde{\nu}_o) \cdot f_L(\tilde{\nu} - \tilde{\nu}_o - \tau)\,d\tau$$

Voigt - Convolution of Gaussian and Lorentzian shapes

# Instrument Overview

$$E_{Mon}(\lambda) = E_{Tx}(\lambda) \cdot R_{BS} \cdot \eta_{Mon}$$




$$E_{Rx}(\lambda) = E_{Tx}(\lambda) \cdot T_{BS} \cdot T_c \cdot T_r(\lambda) \cdot R_{target} \cdot \eta_{Rx}$$

$$T_r(\lambda) = \exp[-K_r(\lambda) \cdot L] = \frac{E_{Rx}(\lambda) / E_{Mon}(\lambda)}{E_{Rx}(\lambda_{ref}) / E_{Mon}(\lambda_{ref})}$$

E - Optical pulse energy

T - Transmission (continuum, resonant, Beam splitter)

R - Reflectivity

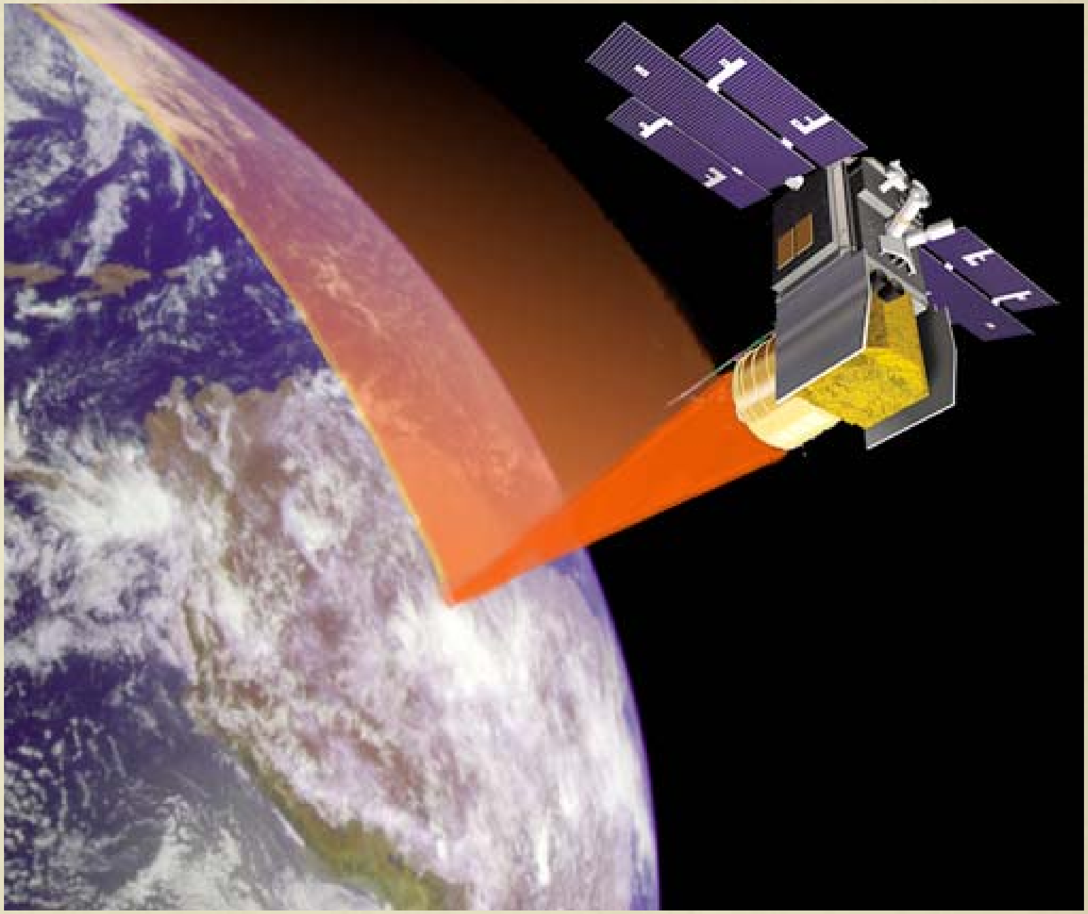
$\eta$ - Detection efficiency

K - Absorption coefficient

- $\eta_{Rx}$, efficiency of the receiver, includes terms often written out explicitly like area of the receiver telescope, the inverse square dependence on range. These terms have been consolidated for clarity

# Laser Requirements

- Spectroscopy
  - Center wavelength 760 - 770
  - Wavelength tunable - ~200 pm
  - Laser linewidth and stability ~5 MHz. (requires >100 ns transform limited pulses)
  - Spectral Purity ~40 dB



- Remote sensing
  - Single Spatial Mode
  - High Peak optical Power (hundreds of watts)
  - Efficient, rugged, lightweight

# Laser Architecture

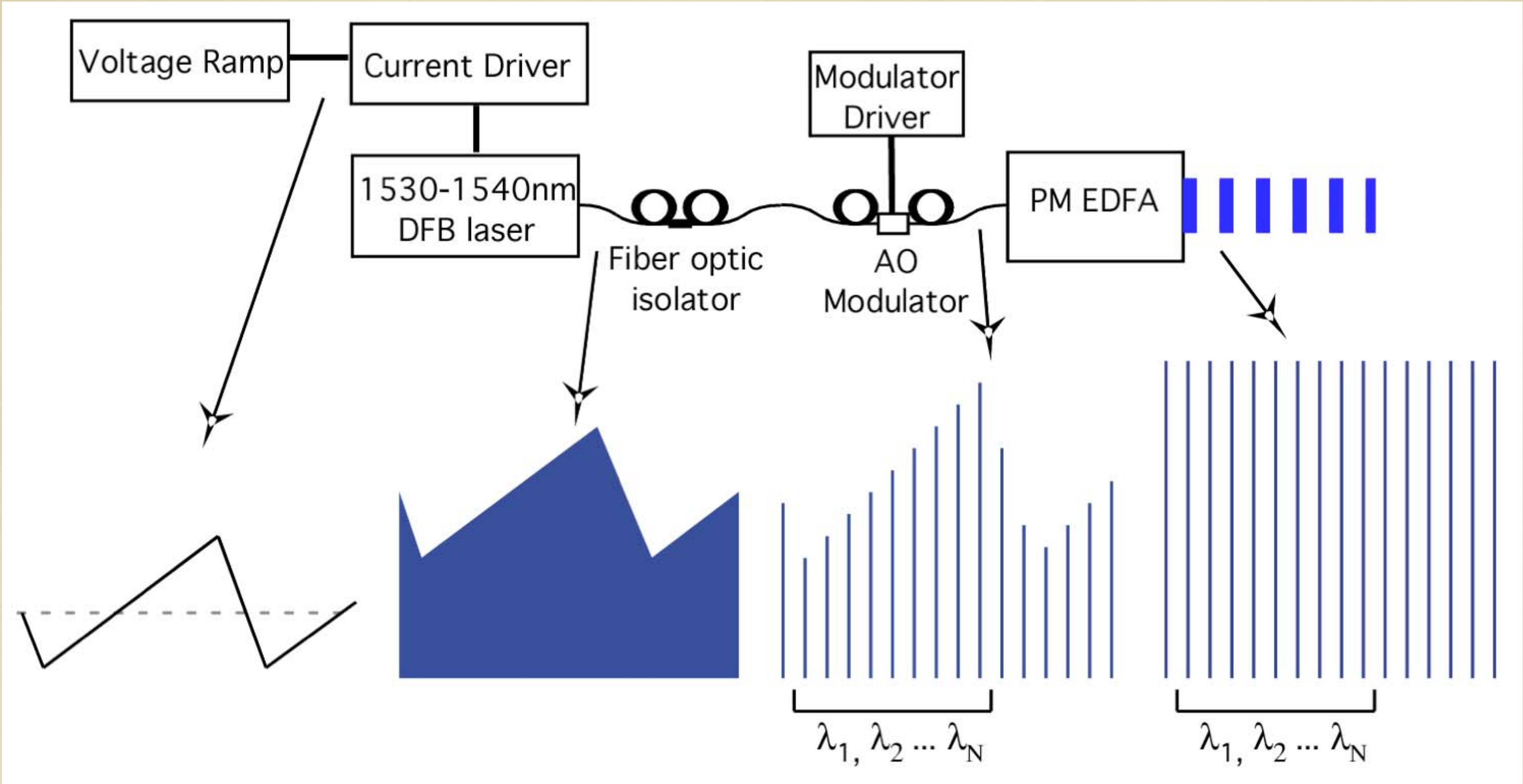
- Distributed Feed Back (DFB) Diode seed laser
  - Narrow band (~1MHz), tunable, fiber-coupled
- Erbium-Doped Fiber Amplifier (EDFA)
  - Efficient, single mode, high power, Polarized
- Periodically-poled (PP) KTP
  - Efficient doubling crystal

*Optics Letters*, **32** (15) 2007

<u>Advantages of Transmitter</u>

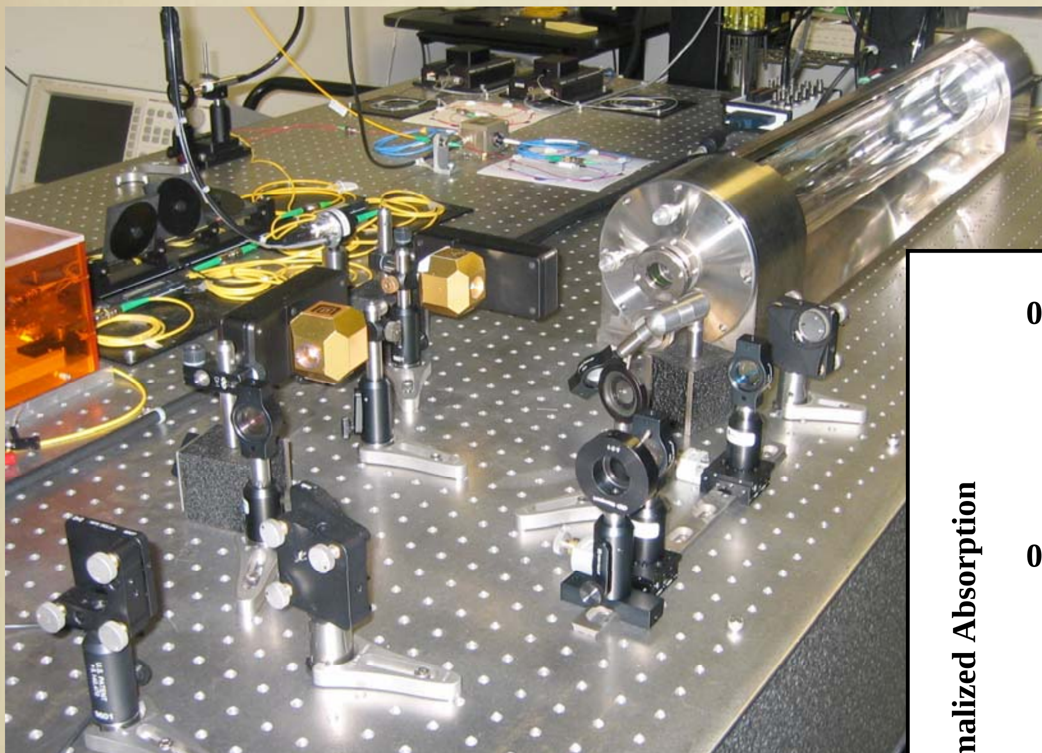
Tunable, narrow-frequency, high-power, single spatial mode, 765 nm, rugged, light-weight, efficient, low parts count, no open cavity, modular

# Modulation Scheme

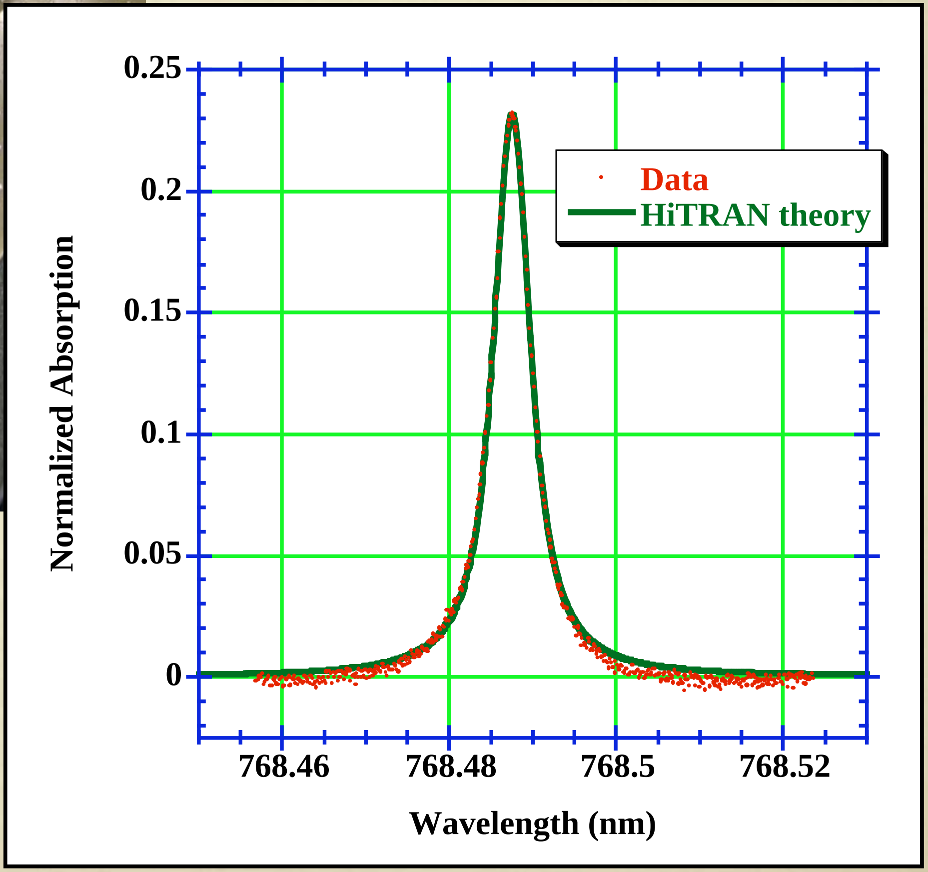



- Drive current to DFB is ramped at ~200Hz. This simultaneously scans the wavelength and the seed power
- The DFB is externally modulated with an Acousto-Optic Modulator (AOM) at ~300 KHz with ~200 ns pulses
- The amplifier is saturated so the amplitude modulation from the DFB current tuning is inconsequential and results in short pulses of roughly equal magnitude and varying wavelength

# O$_2$ Spectroscopy in Gas Cell

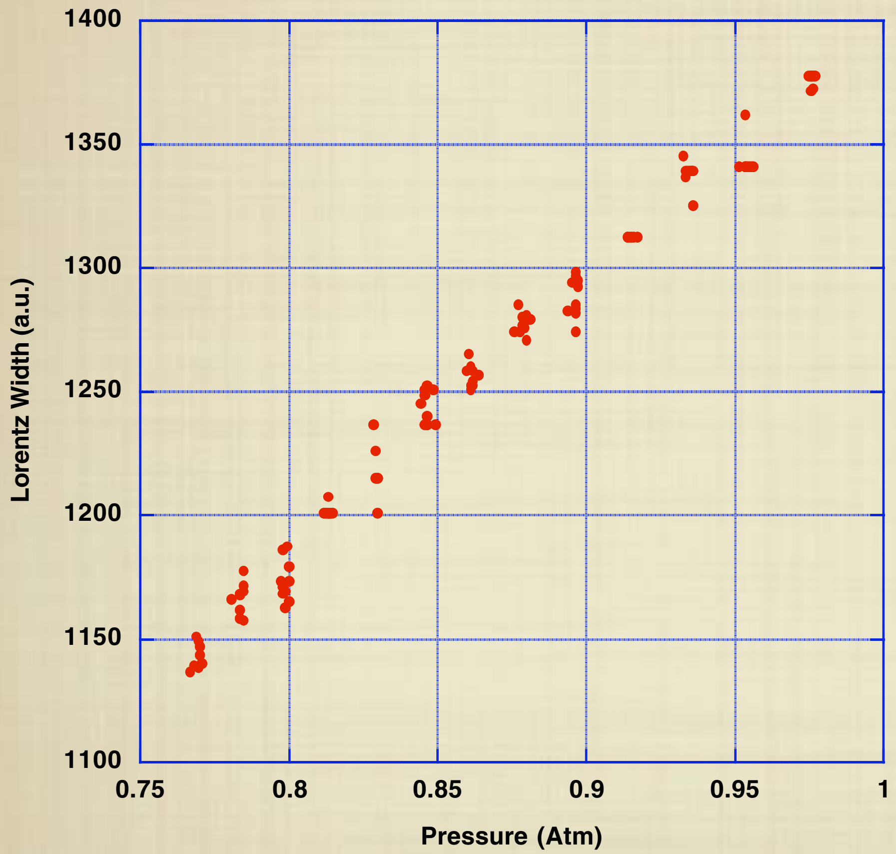


## Atmospheric Absorption



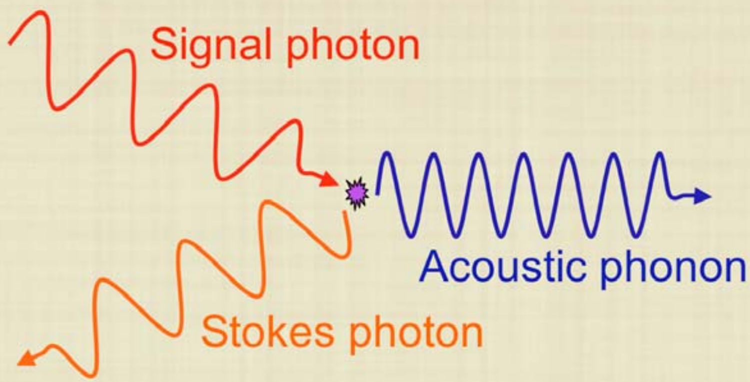

- Absorption of (single scan) transmitted beam through 295 meter (334-pass) optical cell filled with lab air.

# Measurement Demonstration




- Measurement demonstrating the correlation between Pressure and the pressure-broadened (Lorentz component) line-width
- Lorentz width was calculated using a least-squares Voigt fitting routine

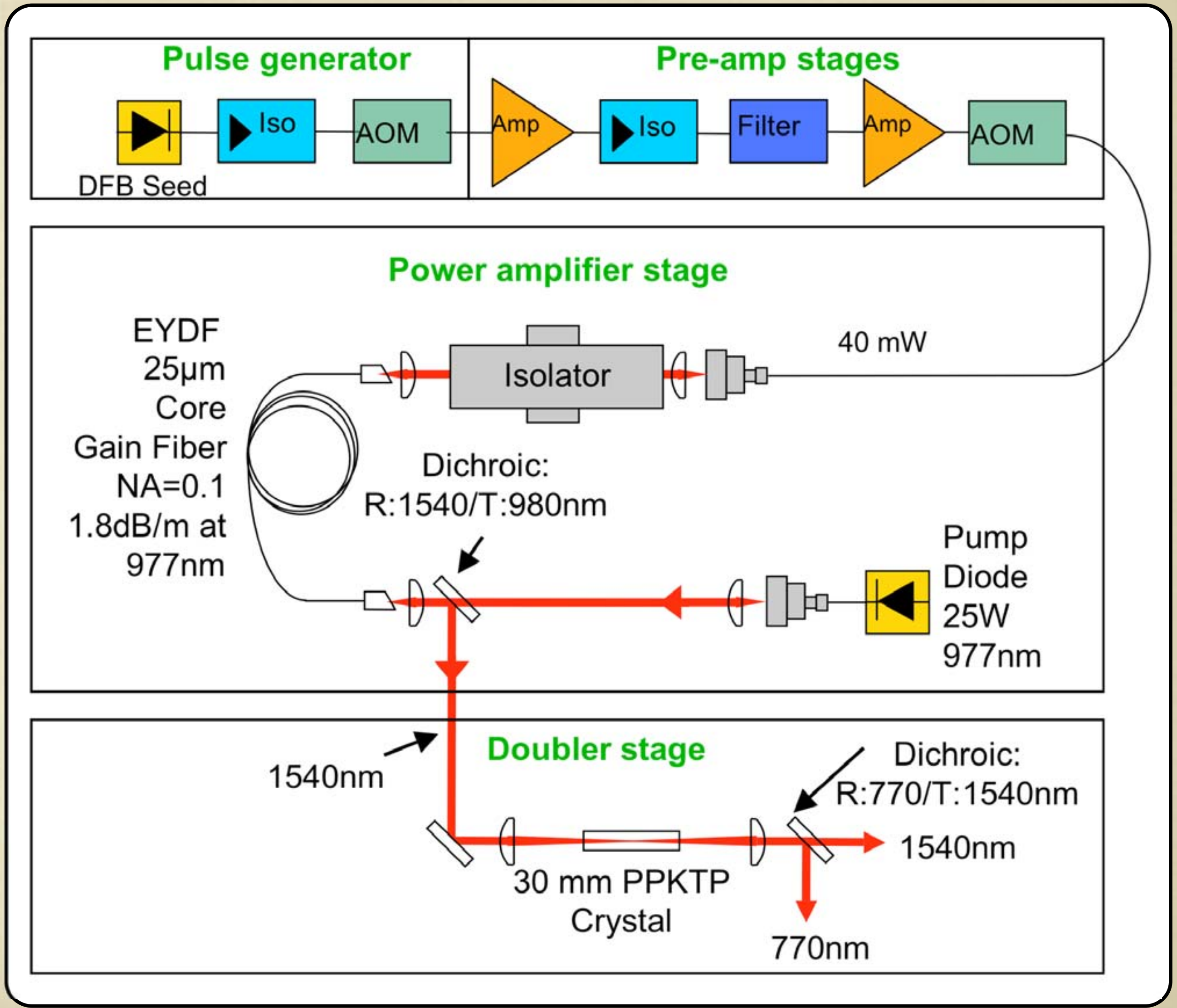
# Stimulated Brillouin Scattering (SBS)




- SBS is a nonlinear interaction between a laser source and sound waves (phonons) in a dielectric medium. It results in a loss of power in the original signal and a backward propagating Stokes signal at a slightly increased wavelength.
- SBS can appear in fiber lasers and amplifiers due to the combination of high optical power, constrained spatial mode and long interaction length. SBS appears in fiber lasers and amplifiers for peak powers as low as ~10W when operating in narrow line-width (<100MHz) AND in CW or long pulse mode.
- The parasitic nature of the SBS signal drains power from the main signal. It is the primary nonlinear affect limiting the performance of the fiber transmitter.

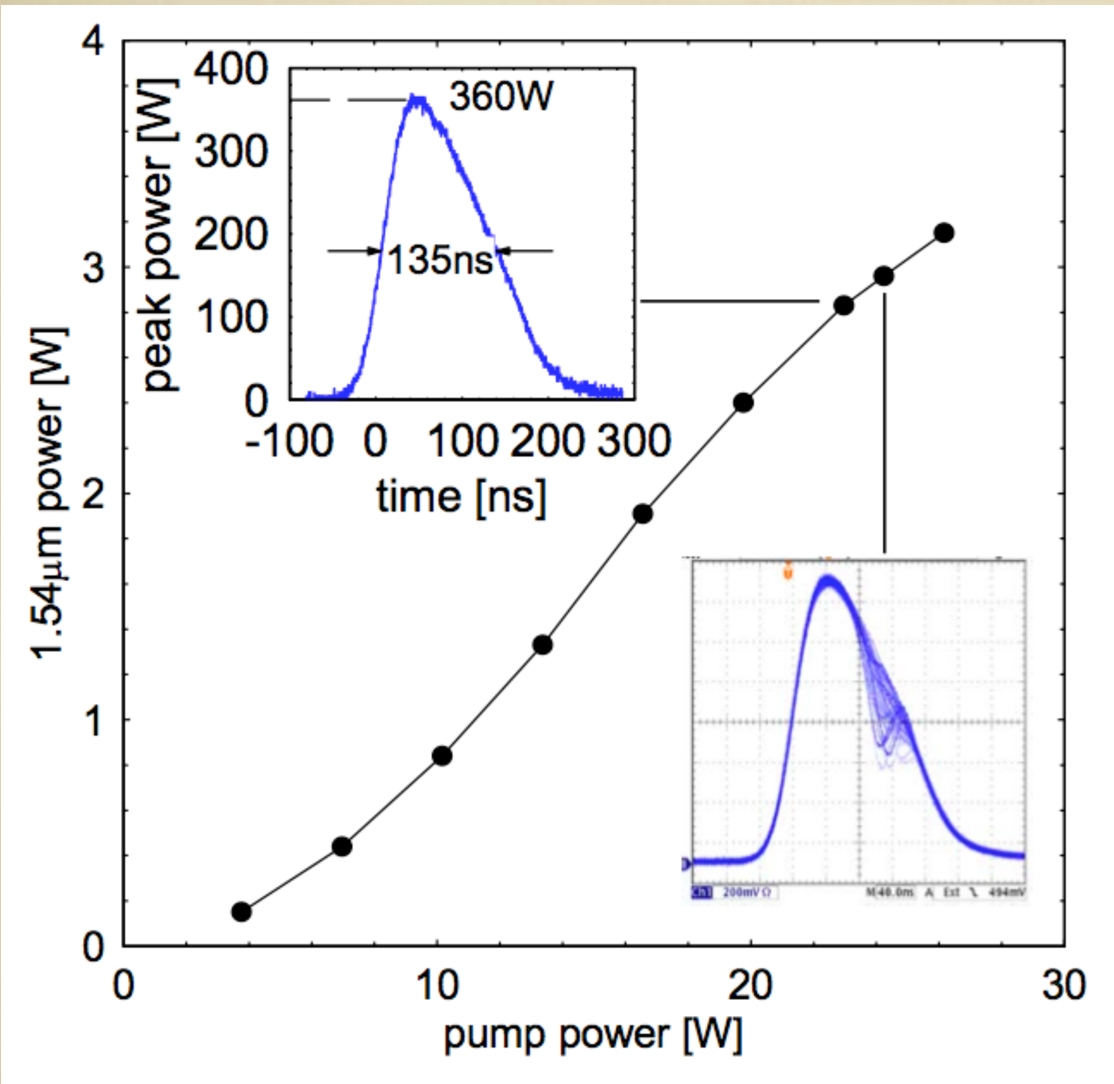
# Laser Lay-out for High-Power Development

- Work done in collaboration with Aculight, Inc.
- Using similar transmitter as a pre-amplifier, we demonstrate higher power
- Additional amp to boost average power at low duty cycle
- Additional AOM to suppress in-band ASE from pre-amp




*Optics Express*, **15** (22) 2007

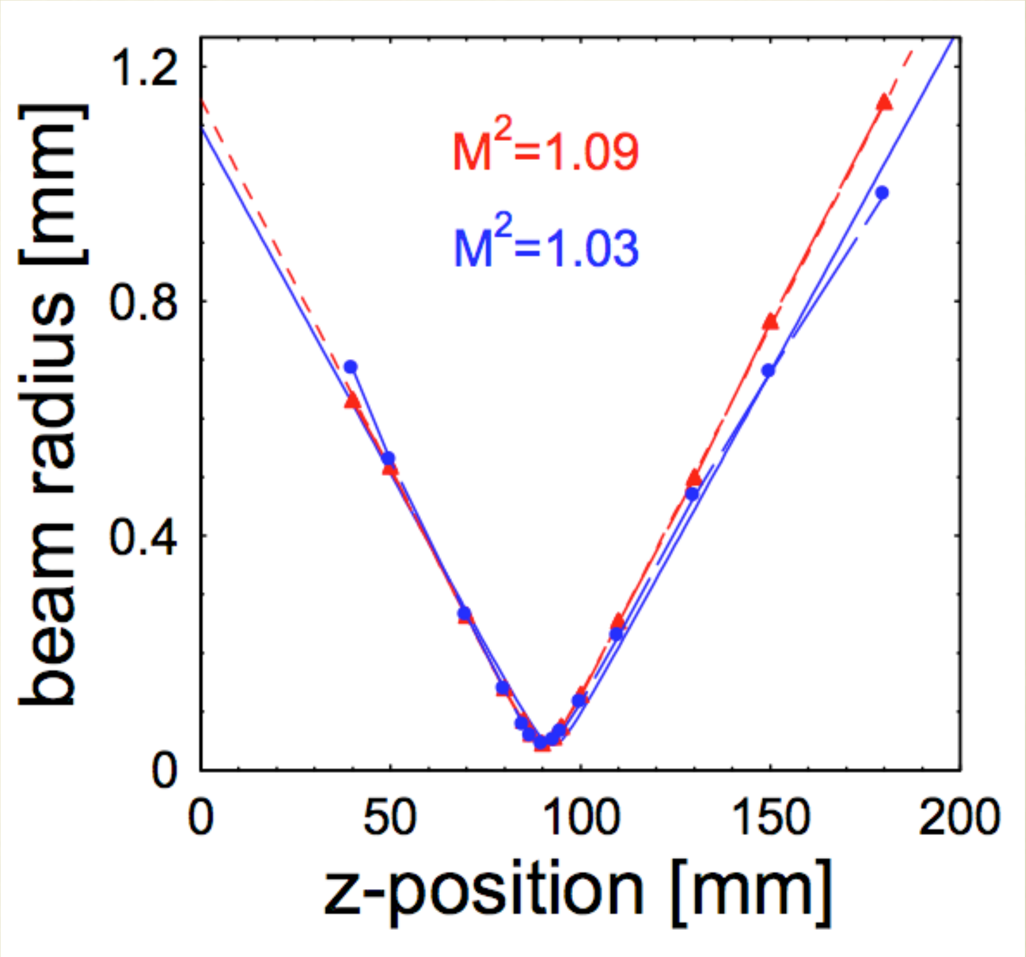
# High-Power Demonstration




- 40 mW average seed power
- 55 KHz PRF
- 360 Watts of SBS-free peak optical power (Highest reported for narrow frequency source)
- SBS is evident above 360 Watts

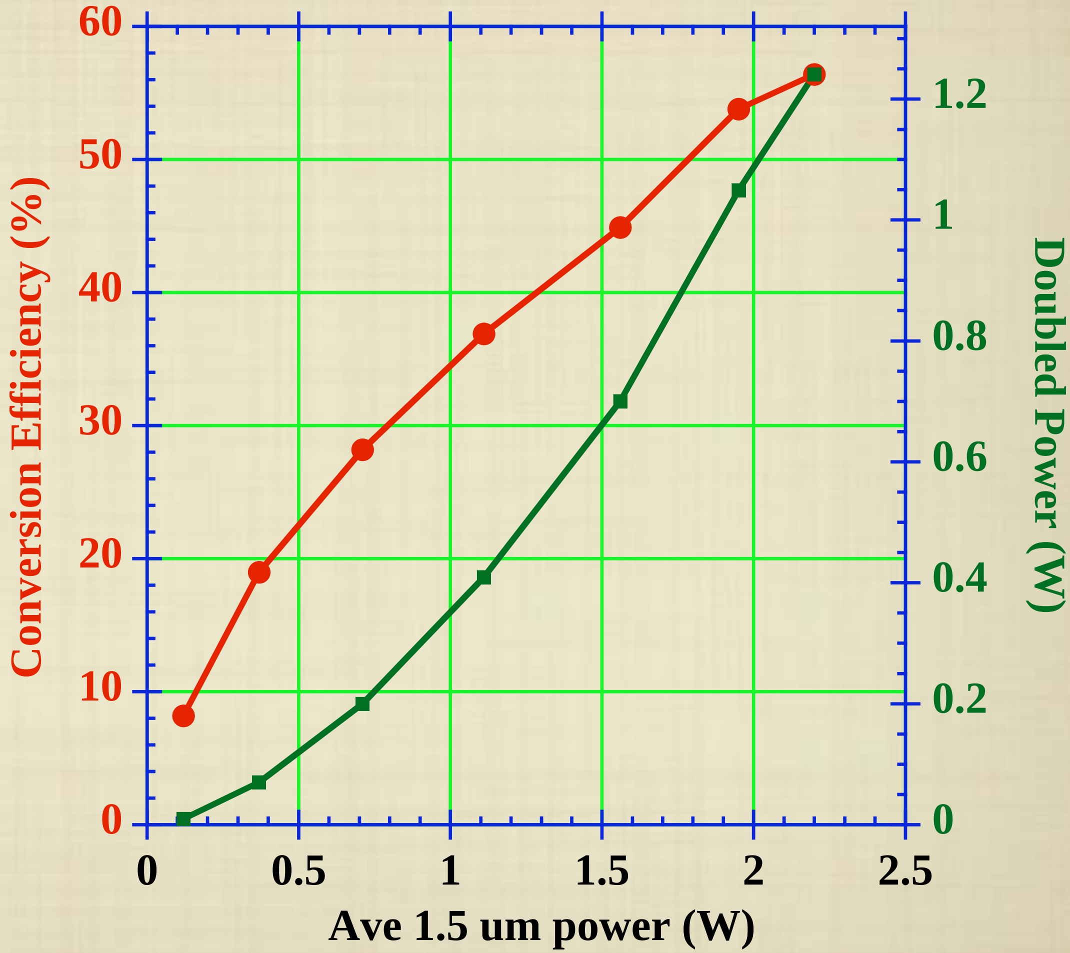
# Spatial Mode Quality

- Near diffraction limited beam quality demonstrated in both axes
- Excellent polarization extinction ratio (20dB)



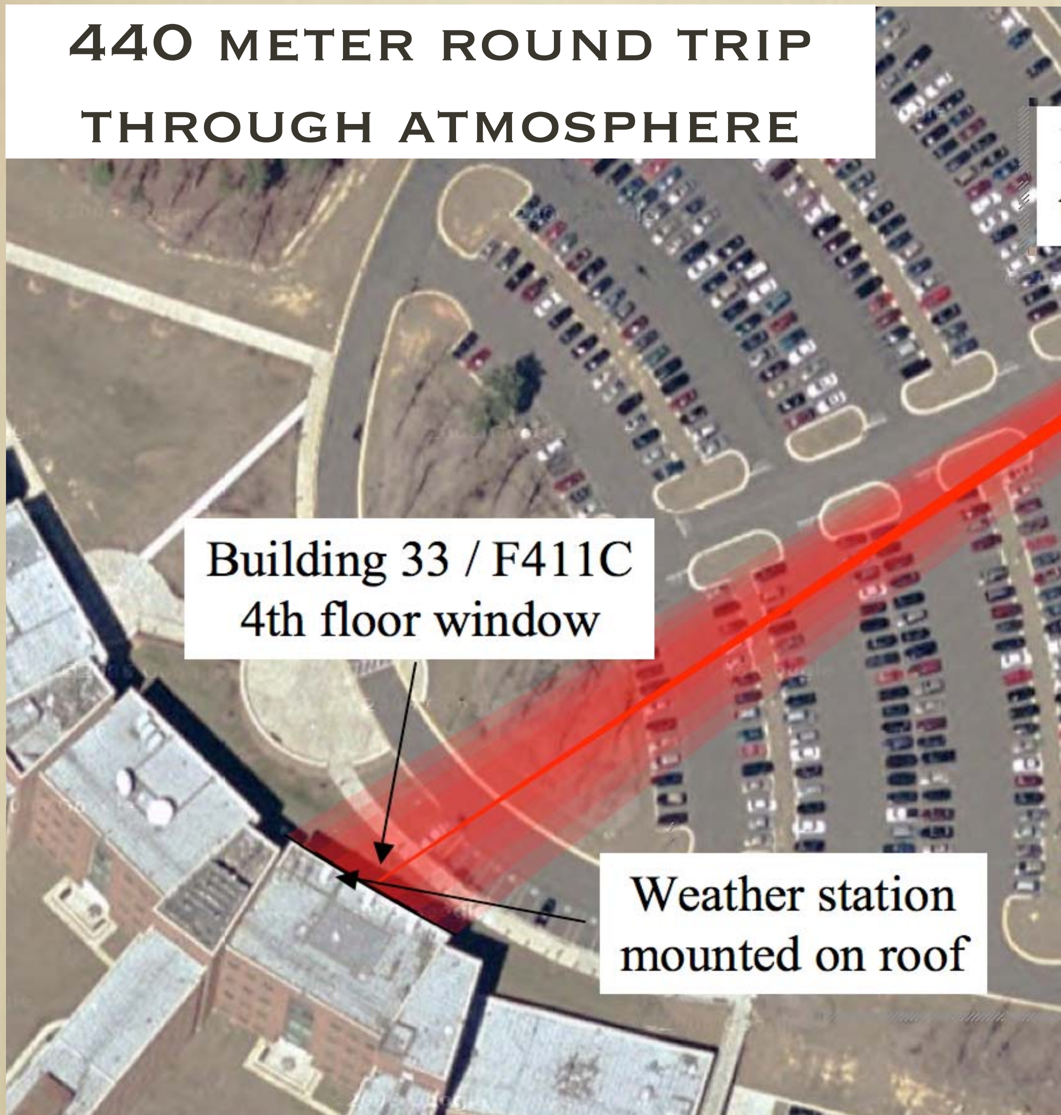
# Frequency-Doubling

- ~265 watts (peak) of Fundamental pump power
- 56% Conversion Efficiency
- ~150 Watts of Peak Optical Power at 770 nm
- <1% Duty Cycle



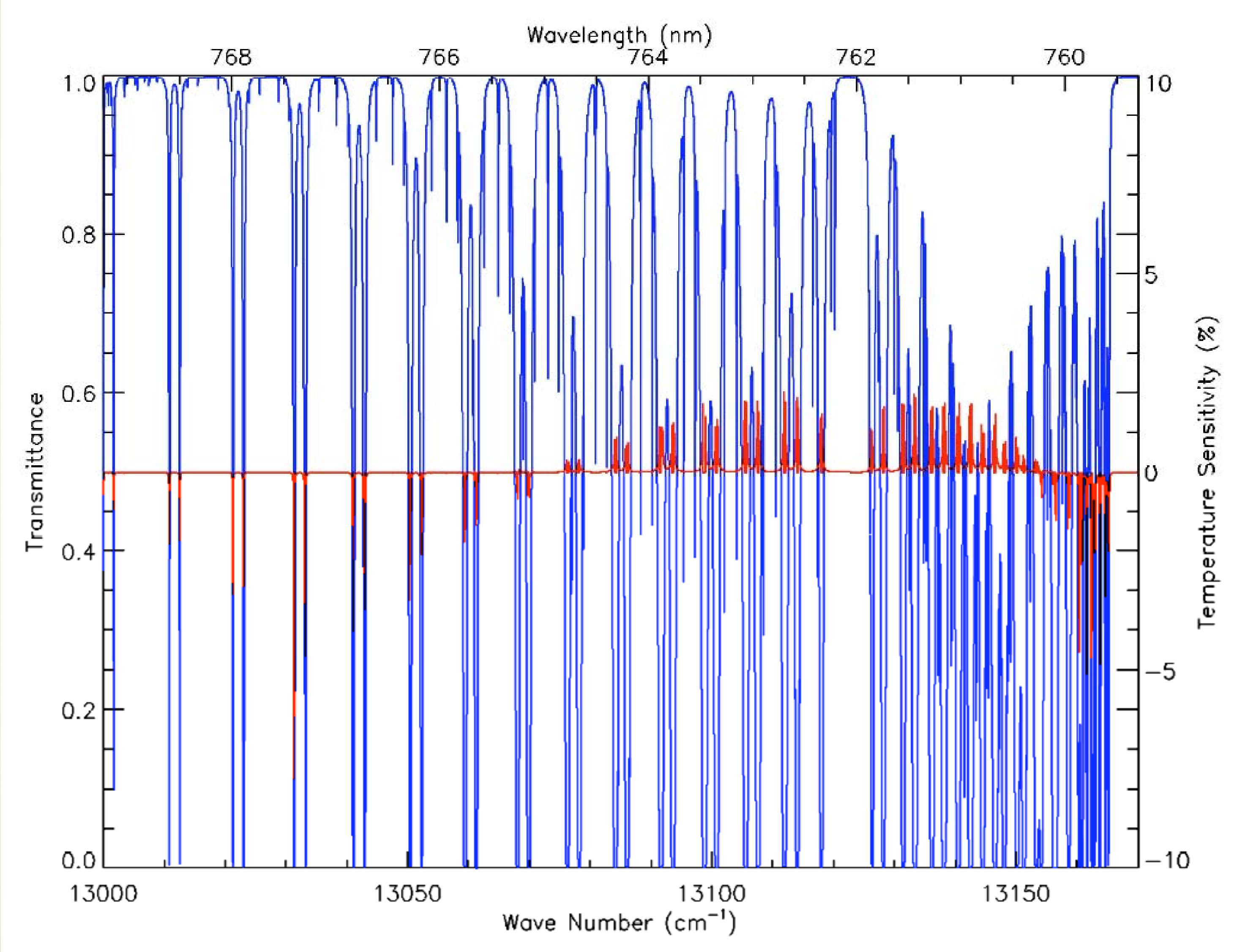
# Aerial View of Open Path

440 meter round trip through atmosphere

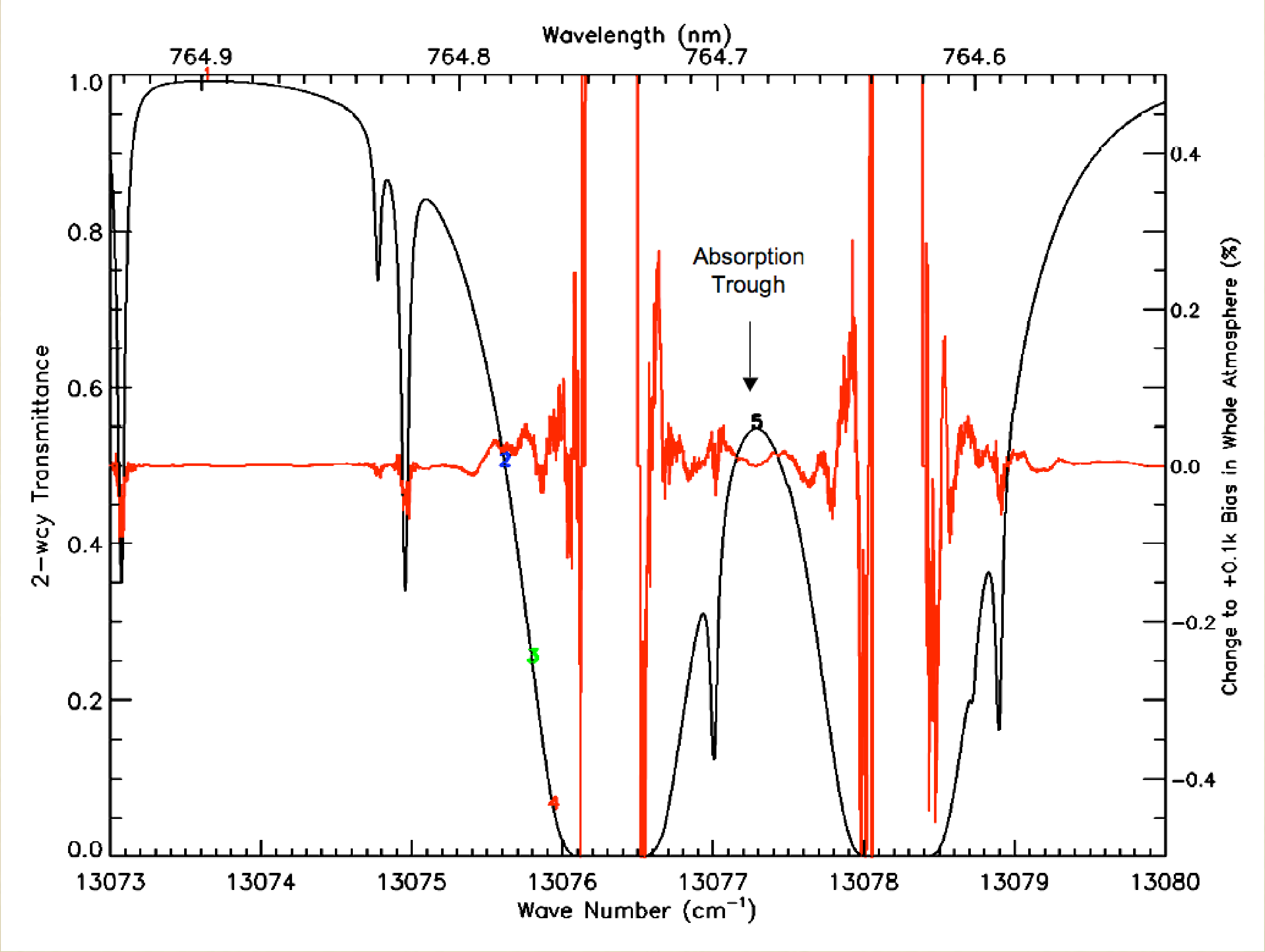



Telescopes pointed out lab window

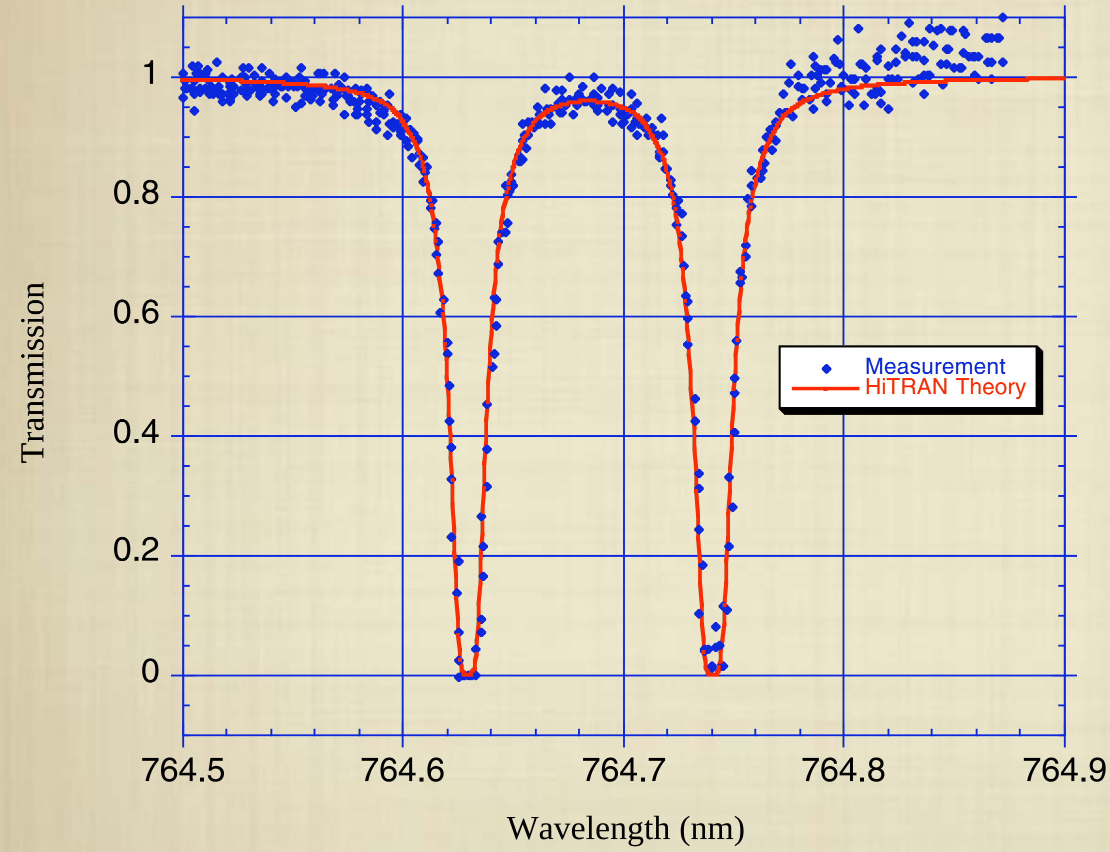
# Temperature Sensitivity



# Temperature Sensitivity



# Open Path Transmission Measurement




- 440 meter open path measurement (slow scan ~1Hr)
- Comparison between measurement and theory calculated with parameters from HITRAN and a coincident weather station
- Measurement taken in desired spectral region

# Future Improvements

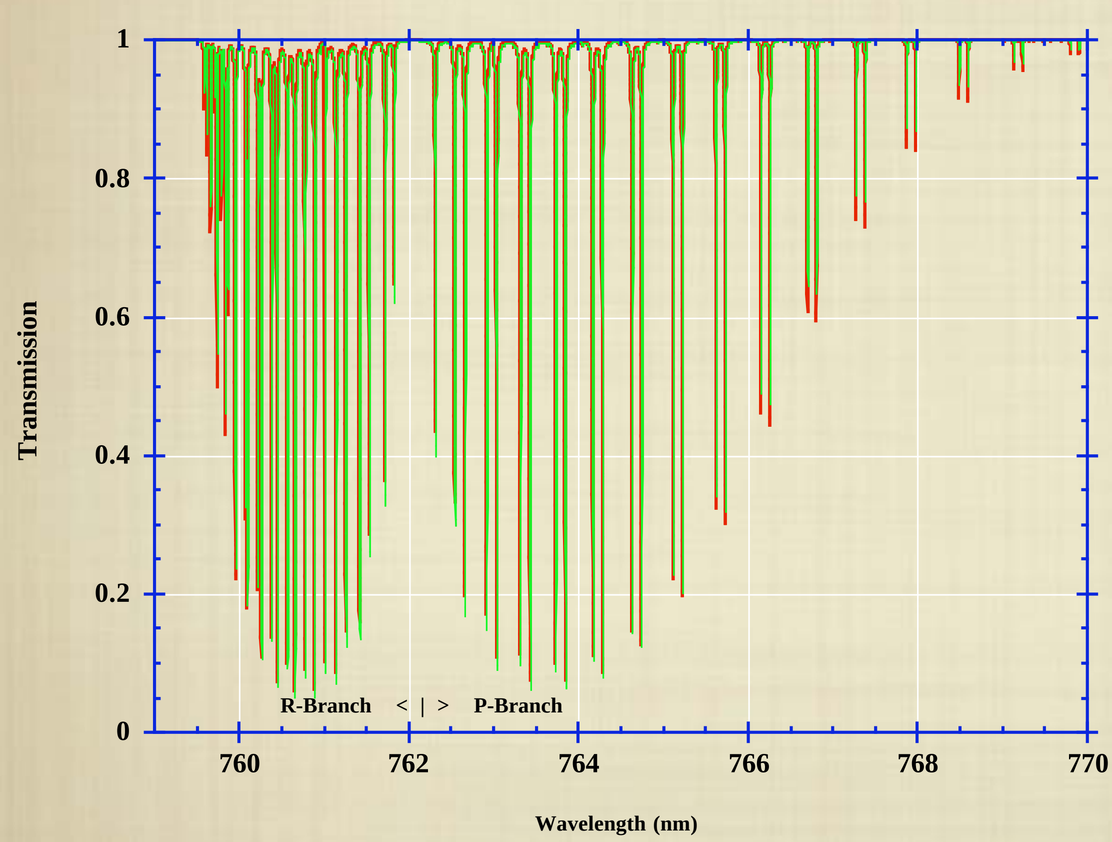
- Faster scanning enabled by pulse integration electronics
- Faster scanning will allow better individual measurements and more averaging
- Improve Instrument data collection and processing
- Improved data analysis software
- More sensitive detectors
- Solar filters
- Longer atmospheric path length for higher absorptions
- Demonstrate atmospheric pressure sensitivity

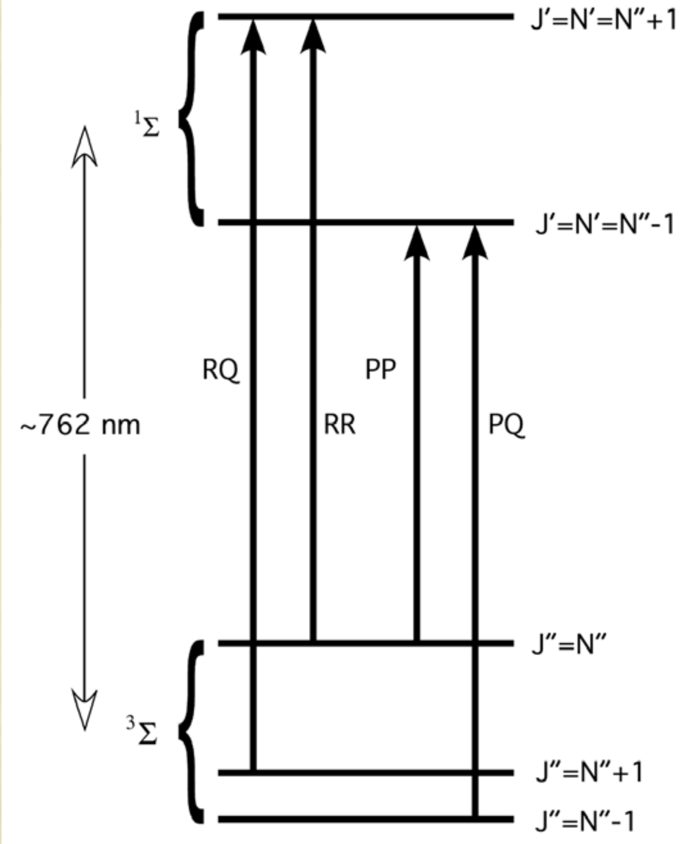
# Conclusions

- Demonstrated fiber-based laser transmitter with: narrow frequency, wavelength tuning, spectral purity, polarized output, single Spatial mode operation, pulse modulation,
- Demonstrated power scaling
- Demonstrated efficient frequency-doubling
- Demonstrated Oxygen A-Band spectroscopy
- Built initial version of remote sensing instrument

# Back-up Slides

# Energy Diagram

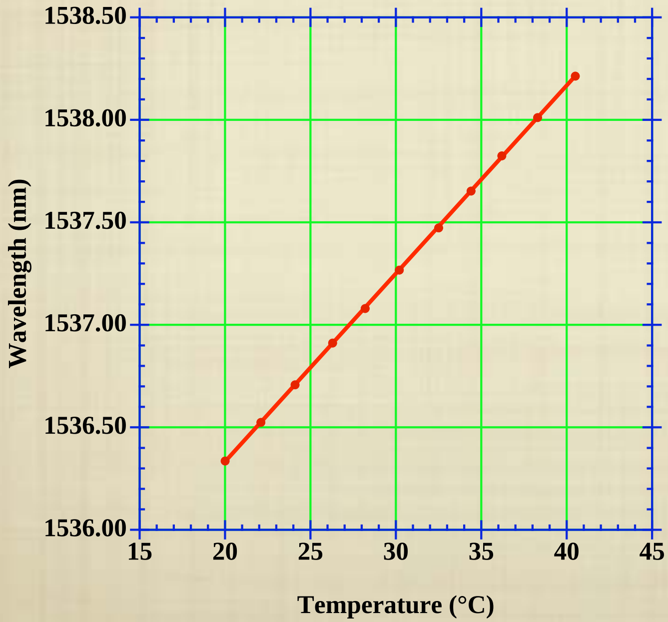


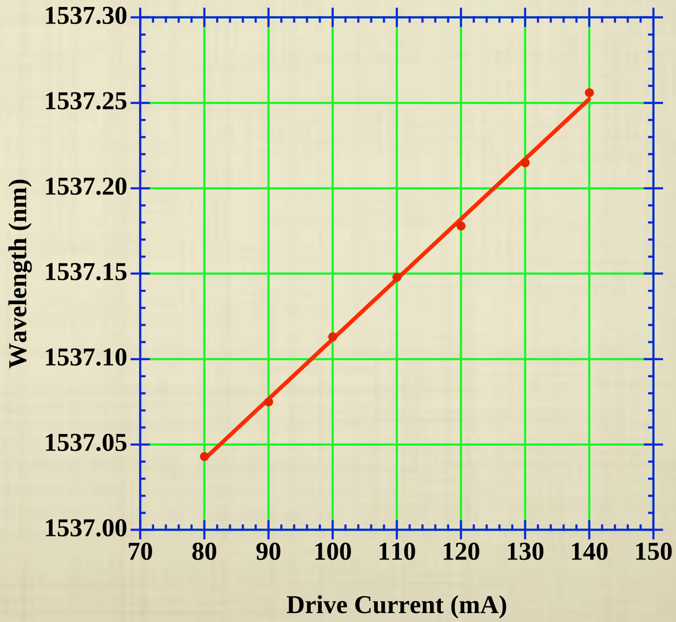



# Wavelength Tuning

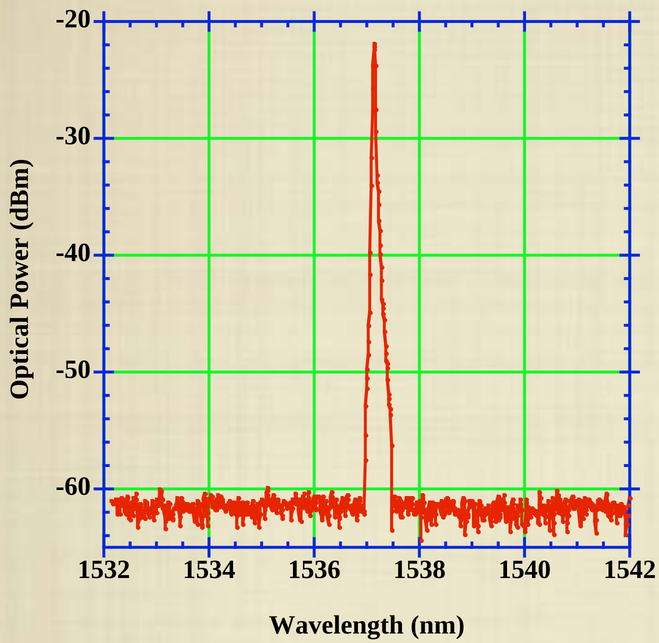
- Temperature setting allows tuning of center wavelength

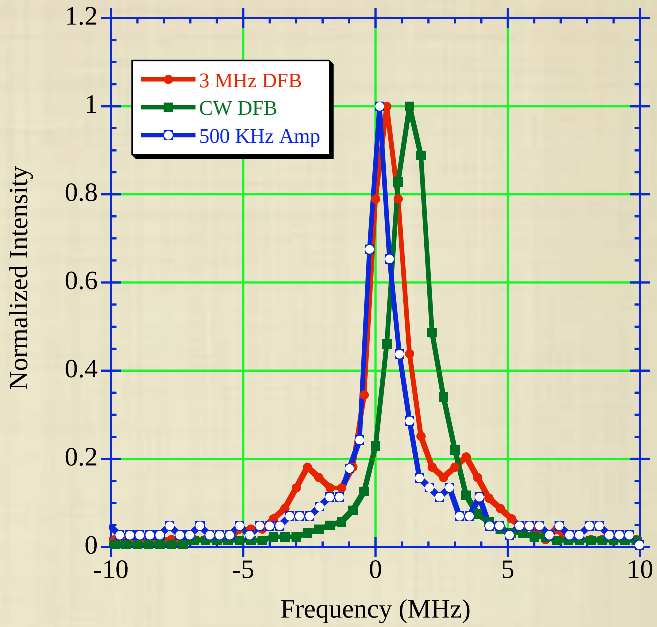
- Current tuning allows faster, more precise wavelength adjustment



# High-resolution Spectral Measurement of Laser Transmitter

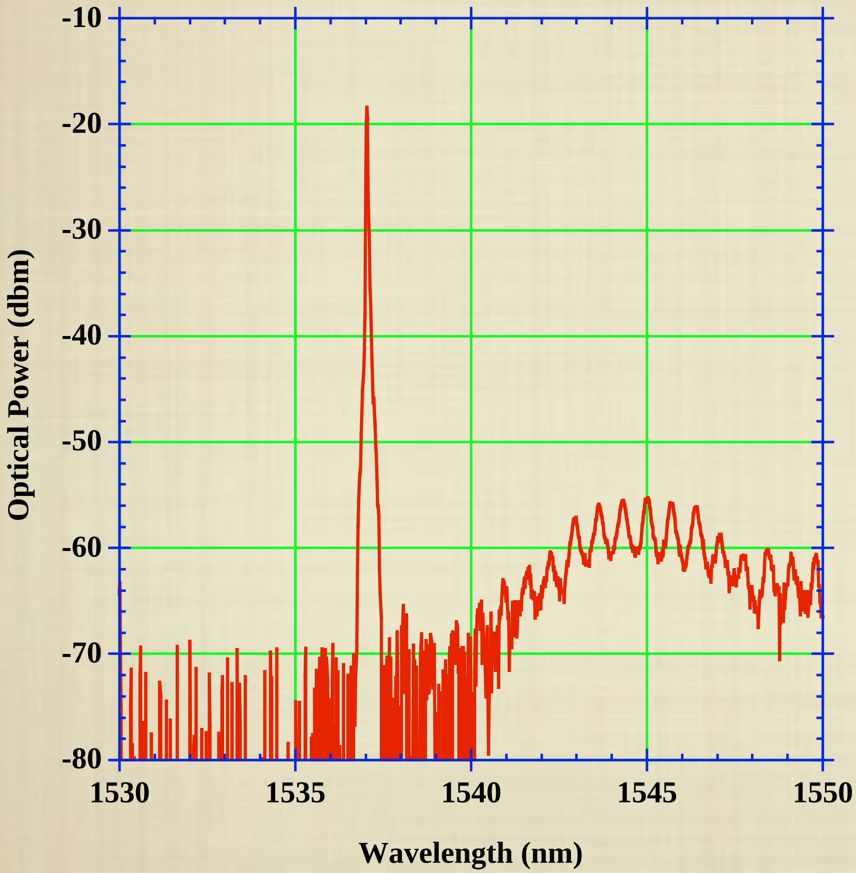



- Measurement of seed laser made with a 50 pm resolution optical spectrum analyzer (OSA)
- DFB seed laser shows 40 dB of side band suppression

- Measurement made with a PZT-scanned fiber Fabry-Perot Etalon
- Red curve shows the calibration scale with 3 MHz side-bands
- Blue curve show that the line-width is not broadened by amplification

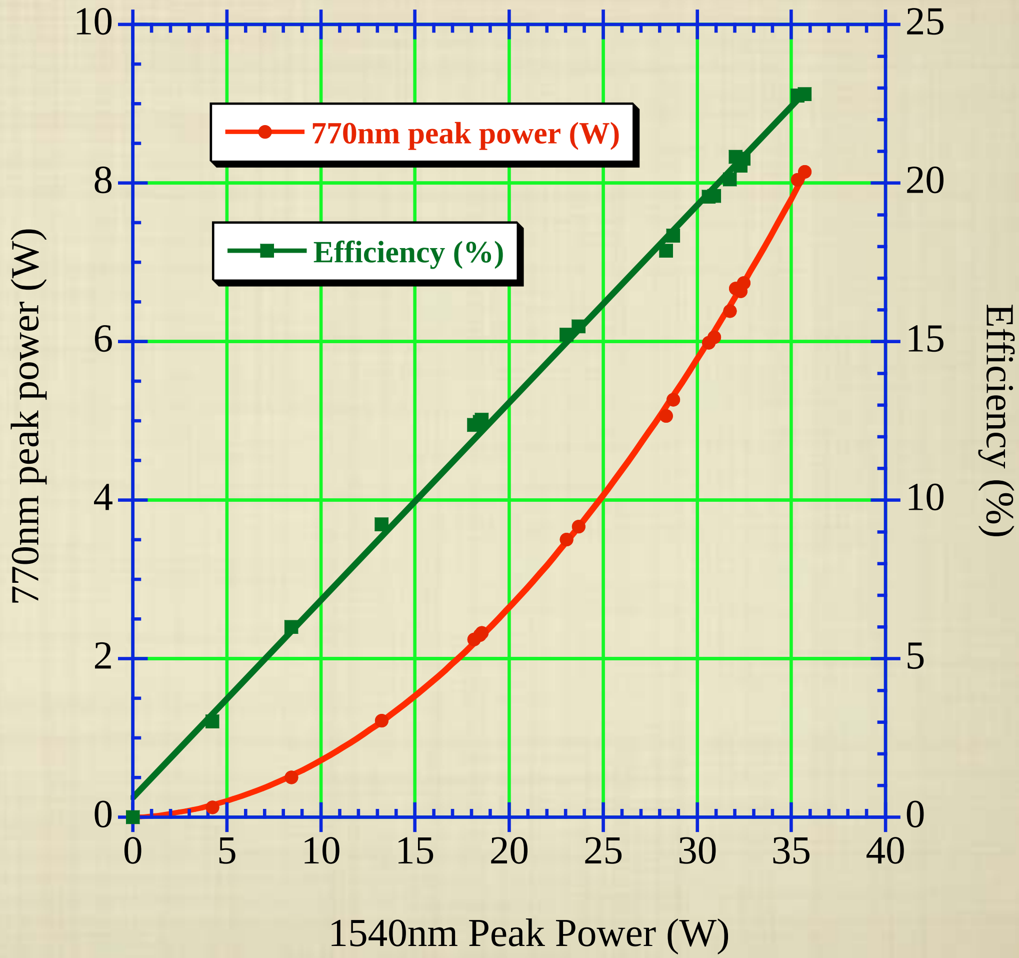
# Spectral Purity




- Measurement of the spectra of the amplified laser signal showing ~40 dB of side band suppression.
- Some residual amplified spontaneous emission (ASE) peaked around 1545 nm is observed. This could be filtered if necessary.
- Additional suppression will result after frequency-doubling

# Frequency-Doubling

- 23% Efficiency
- Frequency-doubling was achieved with a temperature controlled 30 mm PPKTP crystal
- Conversion efficiency is ~1/2 of theoretical limit (for this input power)
- Conversion is primarily limited by power at fundamental wavelength
- Power at fundamental is limited by SBS



# SBS Mitigation in Fibers

$$P_{Th} \propto \frac{A_{eff}}{L_{eff} \cdot g_{SBS}}$$

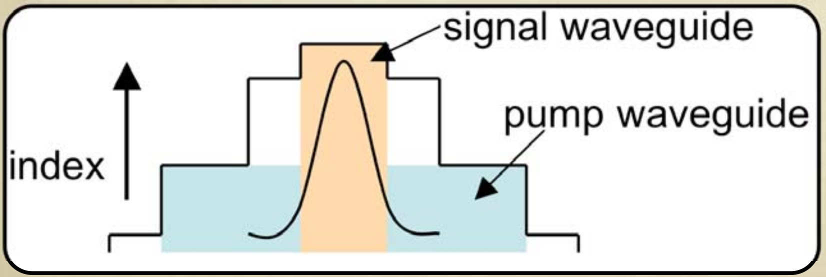
- **Trades**
  - $A_{eff}$ vs. single spatial mode behavior
  - $g_{SBS}$ vs. host, dopants, fiber geometries, spectral width
  - $L_{eff}$ vs. gain, pulse/spectral width

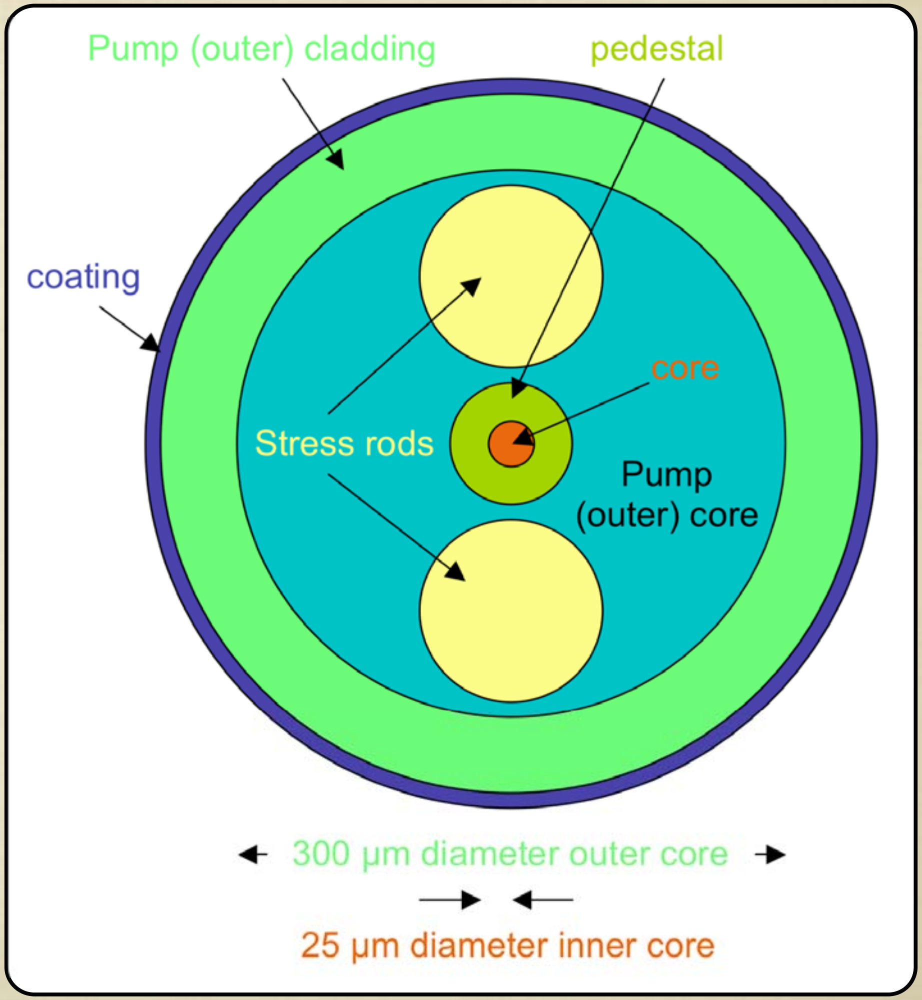
## Common SBS Mitigation Techniques

- Increase fiber Mode Size
- $L_{eff}$ can be reduced by decreasing the laser pulsewidth and/or broadening the signal linewidth . (Our applications require narrow linewidth [long pulses] so this method will not work)
- Decrease fiber length (Increase dopant density to increase gain per unit length.)
- Pump wavelength at highest absorption to increase gain per unit length

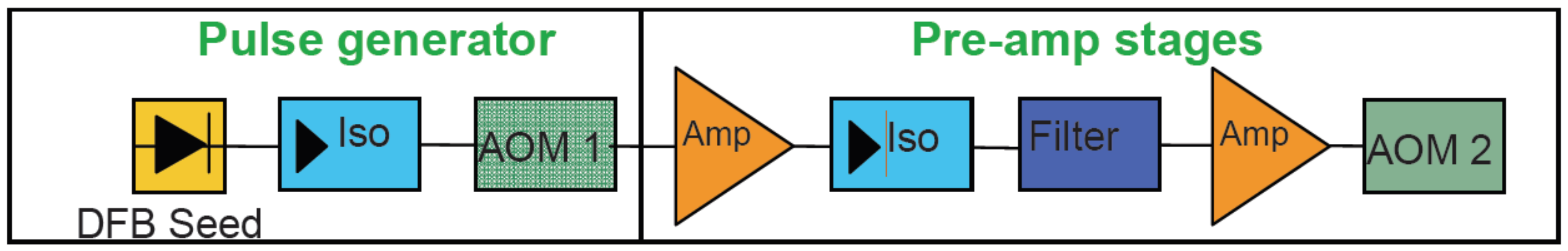
# Fiber design

- Large mode area fiber (25 µm diameter)
- Design optical index pedestal around core to maintain single mode operation with large core area
- Coil fiber to increase loss in higher order modes
- Minimize fiber length
  - High dopant density for high gain per unit length
  - Pump at 977 nm for maximum absorption per unit length



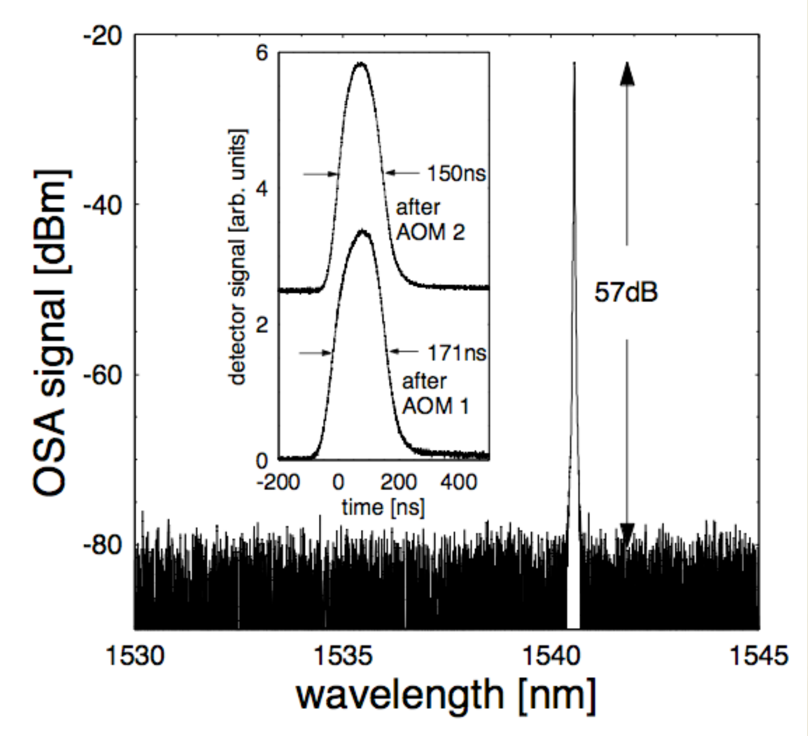



# Seed Source Performance




- Seed Source for low duty cycle (<1%) operation required additional amplifier to boost average power

- Second AOM increased extinction ratio and spectral side band suppression and narrowed the pulse width



# Spectral Purity of Amplified Signal

- Total Amplified signal shows 62 dB of side band suppression
- Insets illustrate the efficacy of second AOM in suppressing in-band ASE